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HUGO MINELL

The Application of Moraine and Till Studies to Ore Prospecting

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THE APPLICATION OF MORAINE AND TILL STUDIES TO ORE PROSPECTING

By

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Doctoral Dissertation

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To Mariann, Sven, and Klara

THE APPLICATION OF MORAINE AND TILL STUDIES TO ORE PROSPECTING

HUGO MINELL

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The genesis of till has been studied in connection with prospecting. Six papers have been published with emphasis on the relation between rock content, grain size distribution, and moraine forms. This problem has been approached by investigating tills in different moraine types within prospected areas with known mineralisations. Extensive use has been made from boulder tracing and chemical sampling. In order to understand the erosion–deposition mechanism during the formation of moraines, glaciological processes and experimental data have been used. The studies indicate that boulders and chemical anomalies resulting from erosion of the underlying bedrock and associated mineralisations vary considerably depending on the glacial environment. Small hummocky moraines reflect well the underlying basement because of an uptransport of material before stagnation of the glacier. In moraineplateaux the situation is less intimate because of an underrepresented erosion during stagnation of englacial debris. In drumlins, subglacial deposition has resulted in a general absence of any direct association between moraine and the underlying bedrock.

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Introduction

Extensive ore-prospecting, including searches for uranium, has been carried out by the Geological Survey of Sweden during the last 8 years. A large range of prospecting techniques has been applied, comprising radiometric, magnetic and electromagnetic surveys from the air, geochemical and radiometric surveys on the

ground, boulder-tracing and geological mapping. Excavations and drillings are the last methods employed in the chain of prospecting operations.

The prospecting has mainly taken place in the inner parts of northern Sweden above the highest shore-line, where the bedrock confining mineralizations is heavily covered with till, which is a product of crushed bedrock. Till is thus the medium in which ore boulders, fine-fraction, metallic anomalies and geochemical and radiometric anomalies indicating mineralization appear. The geochemical, radiometric and boulder-tracing method of prospecting are thus mainly applied to glacial or post-glacial deposits. The main part of this thesis is a review of the results of investigation of tills and moraines, as well as the results of ore-prospecting. The results of prospecting have in many cases improved our understanding of the processes involved in the genesis of tills and moraines.

The till varies widely in composition. This is not always a function of varying rock types but a function of the environmental factors in the glaciated area. The glacier ice has had an erosional effect on the rock surface in some areas and a depositional effect in other areas.

Secondary prosesses have also been of importance in the genesis of tills, especially in areas where till has been transported upwards from the bottom of the glacier and then been left on the ice surface. Since ore boulders and chemical, especially heavy-mineral anomalies are syngenetic with the till, their distribution pattern has been determined by the processes mentioned. Thus, we must also expect to find different moraine forms in different environments.

The six studies listed below treat of problems concerning prospecting and the processes which took place when the till was created, transported and accumulated and when different types of moraine were formed.

1. Minell, H., 1978: Glaciological interpretations of boulder trains for the purpose of prospecting in till. *Sver. Geol. Unders. C 743.*

The characters of boulder trains and chemical anomalies are discussed in this paper in the light of the mechanical properties of the basal part of the glacier ice and the mechanical properties of the bedrock in different pressure environments.

2. Minell, H., 1979: The genesis of till in different moraine types and the deglaciation in central Lappland. *Sver. Geol. Unders. C 754.*

This work describes the morphological features of specific areas with special reference to the results gained from prospecting work. It includes a discussion of the genetic processes in the light of the mechanical properties of glacier ice and theories concerning other soft media.

3. Minell, H., 1973: An investigation of drumlins in the Narvik area of Norway. *Bull. Geol. Inst. Univ. Upsala,* N. S., vol. 5. and

4. Minell, H., 1975: *Drumlinbildning – några fotoelastiska spänningsförsök.* (Some photo-elastic, stress experiments in drumlin formation). *Forskningsrapport 60, Kvartärgeologiska avdelningen, Uppsala universitet.*

These two studies deal with the problem of subglacial erosion and the accumulation of till in the basal part of the glacier-ice-and-lodgement-till complex as a function of different shear stresses. This erosion and accumulation, with glacier ice as one medium and till as another, are discussed.

5. Minell, H., 1977: Transverse moraine ridges of basal origin in Härjedalen. *Geol. Fören. Stockh. Förh. 99*, pp. 270–277.

The possibility of the combined, horizontal and vertical, subglacial transport of bedrock and till, resulting in folding and thrusting, is discussed.

6. Minell, H., 1977: Hog's-back moraines in Harrejokko, northern Sweden. *Geol. Fören. Stockh. Förh. 99*, pp. 264–270.

This paper treats of the upward transport of till material to the surface of the glacier ice, in a case in which surface till has flowed and accumulated in open crevasses.

Discussion

1. Glaciological interpretations of boulder trains for the purpose of prospecting in till.

A number of prospecting projects in Norrbotten have yielded material illustrating the distribution of ore boulders and chemical anomalies. In many cases, there seems to be no connection, as regards the distribution pattern, between a mineralized source and the resulting boulders and anomalies. Furthermore, the distribution or character of the boulder train usually changes because of different topographies and different thicknesses of the glacier ice.

Seven prospecting areas are described here and the interpretations are made on the basis of the mechanical properties of the glacier ice and the bedrock.

Four of these areas show gaps between the mineralized sources and the resulting boulder trains. These areas – Skarjaviken, Labbas, Harrejokko and Västra Kikkejaure – are located in concave terrain and the till consists mainly of local material. At two localities, the boulder trains are connected with their sources. These localities – Nimtek and Västra Rebraure – are also located in concave terrain with a till of mainly local material. One area is presented in which a cluster of chemical anomalies is connected with the source but obviously increases a few kilometres in the distal direction. This locality – Tjärrovare – is located in a convex terrain with a till of mainly long-distance-transported material.

(a) Skarjaviken is located not far from the ice divider and immediately SW. of Lake Tjeggelvas. The till surface is slightly undulating and has no defined, hummocky topography. The results of diamond drillings and trench-diggings show a gap of 200 m between a Mo-mineralization and the proximal part of a boulder train, as well as a chemical anomaly.

(b) Labbas is located not far from the ice divider and SW. of Lake Labbas. The surface is slightly undulating and has no defined, hummocky topography. The results of trench-diggings and diamond drillings show a gap of approximately 60 m between a uranium mineralization and the proximal part of a boulder train, as well as chemical anomalies.

(c) Harrejokk is located not far from the ice divider and NE. of Lake Hornavan. A part of this area is the object with distinct, moraine ridges described in paper 6. The ridges here have generally a transverse orientation in relation to the last ice direction. In the central part of this ridge system, a train of uranium-bearing boulders occurs. This boulder train has a well-defined extension of 300 m. The same distance, 300 m, occurs between the source and the proximal boulders in the train. Only a few kilometres north-east of this object, in the same area, three other

boulder trains of similar character and extension occur. The distance here between the source and the proximal boulders on the till surface varies between 50 and 150 m.

(d) Västra Kikkejaure is located more or less between the ice divider and the highest shore-line NW. of the village of Arvidsjaur. The till surface is undulating and belongs topographically to the peripheral parts of Rogen-like moraines. In the surroundings, ablation tills are common and, in some places, lens-bearing till is present.

The results of boulder-tracing, geochemical investigations and diamond drilling show that the mineralization is located more than 300 m from the proximal, uranium-bearing boulders. However, the chemical anomalies occur much closer to the source.

(e) Nimtek is located between the ice divider and the highest shore-line SE. of the village of Arjeplog. The till belongs to the system of transverse ridges described in paper 2. The ridges have a pronounced morphology, their smallest size being similar to those in Harrejokk and their largest size having the same dimensions as Rogen moraines. The mineralization and the chemical anomalies are connected with each other. Nimtek, like the other areas, is situated in a concave terrain with a till of mostly local material.

Another two areas between the ice divider and the highest shore-line, Västra Rebraure and Tjärrovare, are described.

(f) Västra Rebraure, about 40 km east of Arjeplog represents a till rich in local material and is situated in a regional concavity in the terrain but at the same time on a local convexity in the vicinity of a mineralization and a boulder train. Proximally and on top of this convexity, there is a thick, hummocky moraine with a rough morphology. On the distal side, the till surface is slightly undulating. The boulder train, containing uranium-bearing boulders, occurs close to the mineralization. The boulder train is many kilometres long and is densest in its proximal part.

(g) Tjärrovare is situated on a regional convexity with a quite plane, till surface. The till is mixed with a quite small quantity of local material. A Cr mineralization has given rise to a long train of Cr-bearing boulders and clusters of chemical Cr anomalies, both with extensions of more than 3 km. The boulder train and the anomalies are more indistinct near the mineralization, compared with their distal parts. This happens especially when the plane moraine passes over to a more rough and hummocky moraine.

The boulder distributions in the first four cases ($a - d$) have been interpreted as results of pressure release during deglaciation. The pressure on the basement was high during the glaciation and the strength within rock material and till material was high, which resulted in minor erosion. At the end of the deglaciation, the decreasing pressure resulted in a release of stored, strain energy, which caused fracturing of the bedrock. The relatively low pressure also induced a lower strength in the basement, so that erosion could occur. However, in the peripheral part, the velocity was low and furthermore a probably high, porepressure resulted in low pressure and low shear stresses, which produced no or insignificant erosion, while transport still continued. The process resulted in a boulder train of limited extension and a gap between the proximal boulders and the source. As long as this process proceeds in

a non-eroding stage, these features will be more and more pronounced. When trains of ore boulders and anomalies are connected with the mineralization, as at Nimtek and Västra Rebraure, the pressures and shear-stress conditions must have been favourable for erosion until the glacier ice movement stopped. All these processes took place in concave terrain, which is favourable for a retarding ice movement, and with upward, material transport in the ice, which results in a hummocky moraine with a till rich in local material.

In the Tjärrovare area, the terrain is convex, which caused an accelerating movement and downward transport or only laminar ice flow. This resulted in a flat, till surface with a low content of local material. In the distal part of the Tjärrovare mountain, the topography produced an environment for compressive ice flow which resulted in a cluster of chemical anomalies in a hummocky moraine.

2. The genesis of till in different moraine types and the deglaciation in central Lappland.

During 1973–4, numerous moraine and till investigations were carried out in the interior of northern Sweden. These investigations were combined with the results of the prospecting work and compared with theoretical and empirical models from flume experiments. The purpose of these investigation, which were performed outside the prospecting areas proper, was to get a better idea of the different characteristics of moraines and tills and the relationship between them, both from the topographical and the mechanical points of view. This study is also an attempt to define the different environmental conditions for certain moraines and tills being the media in which ore boulders and chemical anomalies occur.

Areas around Lake Storavan and Lake Uddjaure in the Arjeplog-Arvidsjaur district were investigated by making field observations and stereoscopical interpretations of aerial photographs.

The region can be divided into areas of basal till, long-distance-transported, englacially derived till and supraglacial till formation. Different environmental conditions have produced these different types of moraines.

The basal till is mostly silty and poor in boulders. It appears mainly as drumlinized moraines, drumlin fields and numerous post-crag moraines. At a depth of a few metres, the till usually changes and, with a sharp contact, passes into a water-affected till with, in some cases, lenses of sandy and silty sediments. A low content of local material is characteristic of this till. The basal till occurs where the glacier ice was able to flow through an open terrain.

The composition of the long-distance--transported, englacially derived till is mainly silty and poor in boulders, like the basal till. It usually occurs on moraine plateaux and associated, large-scale, hummocky forms, accompanied by »dead-ice holes». The till is homogeneous but may comprise sediment layers a few metres thick and with a sharp contact with the upper or lower till in the stratification. In the uppermost part, the till contains very little or no local material. Regarding the large-scale topography, the till appears in elevated areas.

The supraglacial tills mainly contain a normal amount of boulders but may also be enriched with them. The predominant grain size varies from fine to coarse, depending on the different influences of the flow processes and the primary content of local or coarse material. The content

of local material varies from very high to quite low. These tills appear in areas where the hilly topography was a buffer to free, laminar, ice flow and in low terrain where compression in ice masses with low velocity could take place.

The formation of different tills and moraines has been interpreted as a consequence of different processes taking place at the base, in the interior of the glacier ice and on its surface.

The basal till was created in an environment in which the till appeared as one medium and the overriding ice as another medium, with a relatively high, velocity difference between them. A shear between the two media may have resulted in the production of water that could not canalize in tunnels, due to the high pressure and high shear stresses in the ice. Such a process would result in a basal melt-out of the ice, which produces a basal, melt-out till. Drumlins and their distribution are probably a consequence of high shear stresses along the contact between ice and till. Tension in the glacier ice may result in longitudinal folding of till material in the basal part of the ice. The glacier ice stagnated at this stage and was thus not involved in any peripheral processes with upward transport.

The long-distance-transported, englacially derived till was probably created in areas where the ice movement, especially in the basal part, was very weak. The low velocity was caused by a large mountain massif or a cool environment, which did not favour free flow. Till-bearing ice could thus stagnate not only in the basal part of the ice but also higher up. In the deglaciation, till melted out and accumulated gradually on the glacier surface, which could lead to the accumulation of considerable deposits. Huge deposits of till probably sank into the ice, resulting in moraine plateaux. The melting water in this quite horizontal, glacier area could result, on the one hand, in sediments and, on the other, in some peripheral areas in erosion channels.

The supraglacial tills were formed in environments where basal material was transported upwards and exposed to the activity of water. These processes took place in concave basins or peripheral parts with compressive ice flow, where the ice was retarded and had a combined vertical and horizontal movement. There was probably a basal freezing, because of low shear stresses as a result of low pressure and low velocity. This freezing contributed a large amount of material to the transport. The supraglacial melting and accumulation resulted in wasting and different types of flow tills. However, washing was not always the only process to give the till a coarse character. A heavy admixture of local material also made a contribution.

The melting of stagnated and broken, glacier ice produced a morphology varying from common, undulating, hummocky moraine to small, transverse ridges, as well as large Rogen-like ones.

From the ore-prospecting point of view, poorly coherent, boulder trains and dispersed clusters of anomalies with different distances to the source can be expected in areas of basal till. This distribution pattern mostly depends on the pressure and shear-stress pattern in the basal part of the glacier.

In areas of long-distance-transported, englacially derived till, no distinct, anomalous pattern derived from bedrock can be expected.

In areas of supraglacial till, very distinct anomalies and boulder trains derived from the local bedrock and mineralizations will be found.

The results reported in this paper support the theory that the erosion was in

general weak throughout the glaciation but quite strong in the deglaciation stage, especially in the peripheral and thinner parts.

Samples from lake-bottom sediments and »dead-ice holes» associated with moraine plateaux were taken for ^{14}C dating in a section measuring 150 km along the direction of ice flow. They indicate an incipient, vegetation development at approximately 8 600–8 700 BP in central Lappland. Unfortunately, the number of samples is statistically insignificant, but all the values obtained are very similar, with differences of only a few hundred years. From these datings, however, it is easy to conclude that deglaciation, with the melting and secondary processes, took place quite fast in the central part of Lappland. In the deglaciation stage, the glacier ice had a more or less horizontal surface, which resulted in stagnations in some areas. The stagnated areas melted away in less than a few hundred years. At some places, ice covered by till was melting when the organic material was carried in.

3. An investigation of drumlins in the Narvik area of Norway.
and
4. Some photo-elastic, stress experiments in drumlin formation.

In 1971, investigations of a type of drumlin were carried out in the high mountains SE. of Narvik in Norway. The drumlins were created on large convexities in a valley. Each drumlin consists of a foliated, basal till, which accumulated in a concave terrain between bedrock knobs. The problem is why the drumlins were created in a convex terrain and between bedrock knobs.

The results of pebble-orientation studies show that the pebbles have an orientation coinciding with the till surface on the drumlins, except for the distal part of each drumlin or close to bedrock knobs.

In order to get an idea of the most important process responsible for the creation of the drumlins, photo-elastic experiments were performed. The models utilised in the experiments were made by pouring a mass of warm gelatine into a plexiglass box. To the bottom of this box, two half-cylinders representing bedrock knobs were attached horizontally. When the gelatine mass had stiffened, the front and back walls were detached and lubricated with glycerine. In the first experiments (paper 4), the model had a contact welded to the bottom of the box. When the gelatine was subjected to manual force and the model was illuminated with monochromatic, circularly polarized light, dark lines (isochromes of a different refringence order) can be observed. The effect is a result of the birefringence of the gelatine, and the refringence order of the isochromes is proportional to the maximum shear stress

$$\tau \max = \frac{\sigma_1 - \sigma_2}{2} .$$

Greater shear stress produces a higher strain rate.

During the later experiments, the bottom was also detached and lubricated with glycerine (papers 3 and 4).

The results of the first experiments with a welded contact indicate high shear stresses at the top of the half-cylinders and low shear stresses at the sides of the cylinders. In the later experiments with a detached bottom, the shear stresses were higher at the top and around the half-cylinders, whilst the low shear stresses were limited to an area between the cylinders. However, when the model was exposed to

only pure, horizontal shear, the low shear stresses appeared in lee or distal positions of the half-cylinders. When the applied force was removed, »crags and tails» were transformed into »precags» and the material-transport direction was reversed in the model. Field observations and experiments show that till can mobilize and accumulate in the basal part of a glacier ice, where probably a certain combination of pressure and velocity exists. The mobilisation will occur in areas with a specific stress pattern. On the other hand, the accumulation will occur where the shear stresses are less than the strength of the till.

5. Transverse moraine ridges in Härjedalen

In 1974, till investigations were carried out in connection with uranium-prospecting in the vicinity of Storsjön Kapell, Härjedalen. In this area, boulder trains and chemical anomalies occurred directly above the mineralizations. In order to explain this very steep, upward transport of material, investigations of different moraine layers were carried out; one is of special interest because of its basal-ridge characteristics. These basal ridges are transverse in relation to the ice direction. The length, width and height are approximately 150 × 80 × 5 m. They consist of a fine sandy till, with folded and thrusted layers of a brittle, volcanic rock. This till layer was covered by a foliated, sandy-till layer. In the whole area, the till is mixed with material of both local and long-distance-transported origins, forming hummocky moraines with different characteristics.

The till is thicker in concave terrain, where hummocky moraines are developed, while convex terrain and hills have a very thin, till cover or no till at all.

The formation of transverse moraine ridges is interpreted as a consequence of a decreasing velocity of the glacier ice in areas with compressive flow. The result of this was that the ice did not glide over the underlying till at a high velocity, but instead the two media (ice and till) flowed more or less together at a low velocity. In areas where the compression was of minor magnitude and of short duration, the frozen till was gently folded. In areas where the compression was considerable and of long duration and where there was a gradual surface ablation, the folding progressed into thrusting. The addition of local material became more and more apparent, the longer the process proceeded.

6. Hog's-back moraines, Harrejokk, northern Sweden

In 1973, investigations of till were carried out in connection with uranium-prospecting NE. of Lake Hornavan in Arjeplog district. A common feature of this district is the occurence of local material in the till. However, in some places, transport went on, without erosion of the bedrock, in the final deglaciation phase. This resulted in a gap between the mineralization and the clastic anomalies, including the boulder train. In the Harrejokk area, the bedrock is covered with an ablation moraine containing mainly local material. The till was in some places affected by water during deposition.

Morphologically, the till appears as a system of small moraine ridges with a length, width and height of approximately 80 × 40 × 6 m. Systematically, the ridges appear in the same system as a cluster of crevasses. The ridge system is situated in a concave terrain. The surrounding moraine type is mostly ordinary, hummocky moraine, except for a plain at a higher altitude, where the

moraine is thick and plateau-like and surrounded by large, water-filled basins.

The till morphology is interpreted as the result of a material transport within the glacial ice with a compressive flow in which pressure, velocity, upward transport and melting were all relatively constant during a certain period of time. Erosion was negligible, due to low pressure, while the movement produced a relatively high rate of material transport. The concave environment and surface melting resulted in the compression and upward transport of material to the surface of a quite thin glacier. This material was increasingly mixed with local material, depending on the duration of the process. During total stagnation and disintegration of the ice, the saturated till could accumulate in the supraglacial fractures.

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